DH Networks - Concept, Construction and Measurement Results of a Decentralized Feed-In Substation

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Abstract

The paper presents the concept and measurement results of a solar thermal pilot plant for decentralized feed-in to a 2nd generation district heating network. Ambitious conditions for both target temperature level and pressure difference are fulfilled with a return line to supply line feed-in (RL/SL) design. The use of water as solar liquid requires an active frost protection using return line district heating water. The stagnation state is investigated by the application of distributed temperature sensing (DTS). The measurement results include one frost protection and almost one feed-in season.

Keywords: solar thermal, decentralized feed-in, stagnation, frost protection, control concept, measurements

1. Introduction

Decentralized feed-in of solar thermal gains can contribute to the decarbonisation and flexibilisation of modern district heating networks (e.g. Heymann, et. al., 2017). The development of standards concerning network feed-in substations and their control concepts is the research goal of the ongoing research project "Kostenreduktionspotential beim Ausbau der Solarisierung von Fernwärmenetzen durch Standardisierung"[1]. These standards are derived from practical experiences of the planning, the commissioning and the operation of pilot plants – including the solar thermal system and the substation itself – as well as simulations studies.

In this paper the design and control concept of a pilot plant is presented which is in operation at the Centre for Energy Technology (CET) in Dresden since November 2016. The network feed-in substation is connected to a 2nd generation network (according to Annex X classification Rosa, et. al., 2014) and was developed in cooperation with the local network operator as part of a feasibility study for larger collector fields. The pilot plant is designed for the RL/SL feed-in into the district heating network - the most common and most flexible type of decentralized network integration.

This paper presents detailed measurement results and details of the control algorithms for the three main operation modes (hereafter referred to as states) of the network feed-in substation:

• *Feed-in* of solar energy,

• *Stagnation* and

• Active *Frost Protection* for the water-based solar circuit.

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2. Concept of the District Heating Network Feed-in Substation

The pilot plant is connected to the primary district heating network of the city with a nominal pressure stage of PN25 and the nominal target feed-in temperature is 110 °C. Therefore solar vacuum tube collectors working according to the heat pipe principle are used in the collector field (CF). The collector field consisting of six subfields C1..C6 has a total gross area of 84 m² (total aperture area 48 m²) and an inclination of about 31° facing south. The design heat flow rate is 30 kW based on a total incline irradiance $G_{t,i}$= 1000 W m^{-2} and collector field temperatures of 115/70°C. The subfields C1..C6 are connected in series (see Fig. 1).

The circulation pump in the solar circuit Pu_{STS} is a speed-controlled pump group where only one pump is used in main operation at a time and where the other pump is hold as a spare component. The redundancy is important to guarantee the functionality of frost protection. The compressor-based pressure maintenance is connected to the system in the supply line of the collector field through stagnation cooler. This cooler is built as a finned tube radiator which limits the maximum steam spread in case of stagnation, reduces the design volume of the common additional auxiliary vessel and thereby the design volume of the pressure maintenance expansion vessel.

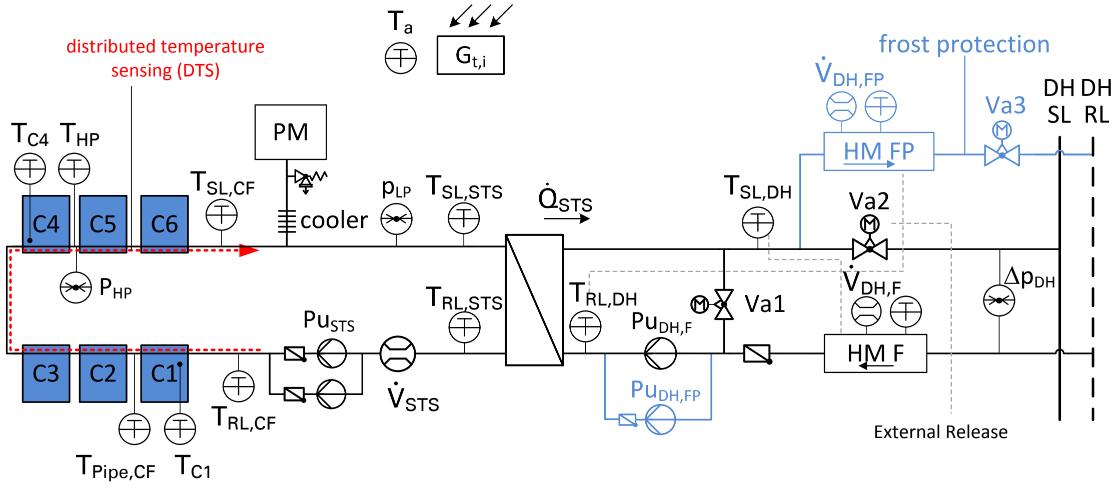

Fig. 1: Schematic of the feed-in substation (Ta – ambient temperature, C – collector, CF – collector field, DH – district heating, HM – heat meter, F – feed-in, FP – frost protection, HP – highest point, LP – lowest point, PM – pressure maintenance, Pu – pump, Va – valve, STS – solar thermal system)

The speed-controlled feed-in pump $Pu_{DH,F}$ is necessary to overcome the pressure difference Δp_{DH} in the DH network and generates the feed-in volume flow. The proper selection of this component is essential to assure the feed-in of the solar yields into the network. This is often complicated due to the lack of information about Δp_{DH}, $T_{SL,DH}$ and $T_{RL,DH}$ at the feed-in point for the course of the year and the future development of these values. Before feed-in the bypass valve Va1 will be opened to heat up the medium in the district heating side of the substation to prevent cold plugs in the network but will be closed during feed-in. It can also be opened during times of partial load/low irradiance to raise the RL temperature $T_{RL,DH}$ when the speed-controlled pumps reach their minimal flow rate. The valve Va2 is used to realize an external unblocking. If necessary the network operators can withdraw the release signal and prevent/stop the feed-in by closing the valve and shut of the pumps. The valves Va2 and Va3 are used to switch the flow direction between RL/SL in the state *Feed-in* (Va2 open, Va3 closed) and RL/RL for heating the STS in the state *Frost Protection* (Va2 closed, Va3 open). A separate frost protection pump $Pu_{DH,FP}$ is used because of different design parameter for the RL/RL frost protection heating (low discharge head) and due to redundancy.

A minimum sensor equipment is necessary for the plant operation. It consists of five temperature sensors ($T_{SL,CF}$ $T_{SL,STS}$ $T_{RL,CF}$ and $T_{SL,DH}$, T_a), the radiation sensor $G_{t,i}$ as well as two heat meters. The heat meter HM F measures the heat fed into the network. The volume flow signal $\dot{V}_{DH,F}$ of the feed-in heat meter is used for a control loop by an analogue module. There is a second heat meter HM FP, which measures the heat required for frost protection. These two separate heat meters are necessary as long as no bidirectional heat meter is available on the market that is certified for billing.

The monitoring package consists of additional temperature sensors, three pressure sensors (p_{HP}, p_{LP}, Δp_{DH}), a flow meter $\dot{V}_{STS}$, as well as a distributed temperature sensing system (DTS see Herwig, Rühling, 2014). The DTS uses an optical sensor cable, which is attached to the collector pipe of the system in order to measure the temperature distribution with a high spatial and time resolution. This is helpful for detailed analysis of the states *Frost Protection* and *Stagnation*.

3. State Feed-In

3.1 Controller

In order to operate the network feed-in substation in the *Feed-in* state a set of three controllers is used (see Tab. 1). The controller C1 is used for the matched-flow control of the collector field output temperature $T_{SL,CF}$ by adapting the pump speed of Pu_{STS}. This controller compensates changes mainly in the radiation $G_{t,i}$ and the return line temperature $T_{RL,STS}$. The objective is to keep the heat exchanger input temperature $T_{SL,STS}$ higher than the setpoint of the feed-in temperature $T_{SL,DH}$ – to guarantee heat transfer – and to keep the average temperature of the solar thermal system low to minimize losses.

Tab. 1: Closed-loop PI-controllers for state Feed-in

Name	Control variable	Setpoint	Output
C1	$T_{SL,CF}$	115..120°C	speed Pu_{STS}
C21	$T_{SL,DH}$	110°C	setpoint C22
C22	$\dot{V}_{DH,F}$	results from control signal of C21	speed $Pu_{DH,F}$

The two general main tasks of controlling the feed-in pump $Pu_{DH,F}$ are:

- to guarantee a stable volume flow $\dot{V}_{DH}$ despite the strongly changing pressure difference of the network Δp_{DH} but corresponding to the current solar yields and
- to operate with minimal power consumption.

A cascaded controller is used (see Fig. 2 left) to achieve both tasks. The temperature controller C21 finds a solution for the equation (eq. 1) by adjusting the volume flow setpoint $\dot{V}_{SP}$ of the controller C22 and thereby the volume flow $\dot{V}_{DH}$. The inner controller compensates any change of the pressure difference of the network $\Delta p_{DH.}$ This is energetic efficient, because the pump speed is changed to manipulate $\dot{V}_{DH}$ directly instead of using a throttling or bypass valve. The volume flow signal of the heat meter HM F can be used directly e.g. through an additional analogue module, depending on the kind of heat meter and the achievable update interval. The tested substation works well when controllers are updated every four seconds.

$$T_{SP} = T_{SL,DH} = \frac{\dot{V}_{SP} \cdot \varrho \cdot c_p}{\dot{Q}_{STS}} + T_{RL,DH} \text{ with } T_{SP}.. \text{setpoint for } T_{SL,DH}, \dot{V}_{SP}.. \text{setpoint for } \dot{V}_{DH} \quad \text{(eq. 1)}$$

The compensation of the variable pressure difference Δp_{DH} by using the volume flow controller C22 (see Fig. 2 Right) is realized in three steps:

1. The setpoint volume flow is reached at the actual pressure difference $\Delta p_{DH,1}$ (steady state)
2. The volume flow $\dot{V}_{DH}$ differs from the setpoint as a result of the disturbing pressure difference $\Delta p_{DH,23}$. The feed-in temperature $T_{SL,DH}$ will differ from its setpoint as well. (instationary)
3. The controller C22 compensates the pressure difference variation and the feed-in temperature will not be affected. (stationary)

The volume flow signal $\dot{V}_{DH}$ of the HM F can also be used to find the right pump speed to overcome the pressure difference Δp_{DH} when the feed-in starts (Rosemann, et. al., 2017a). The integration of this signal into the plant control as described above is recommended because of the low additional costs for reading out this signal and the high advantages for solving the common technical pressure difference Δp_{DH} problems in district heating networks (Lennermo and Lauenburg, 2015).

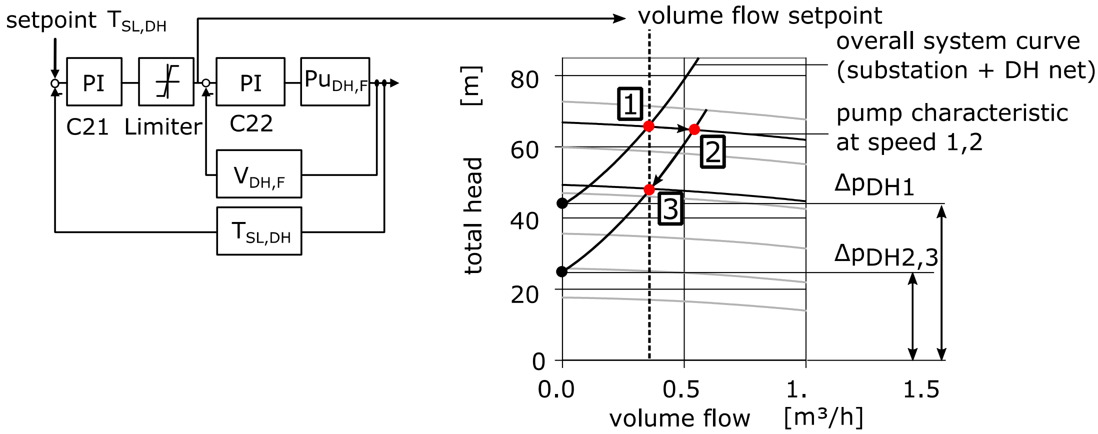

Fig. 2: Left: Cascade controller for the feed-in temperature TSL,DH
Right: Characteristic curves of the feed-in pump PuDH,F and the operation points 1..3
during the control action of C22 reacting on a step of ΔpDH
(1 – Starting point, 2 – after step of ΔpDH without reaction of C22, 3 – Final stage after correction of the pump speed)

3.2 State Machine

For the correct operation of a district heating network feed-in substation, the controller and actuators of the plant have to be de-/activated and set to corresponding values at the right moment. This task is solved with a state machine (see Fig. 3). A state is a set of actor and controller settings which structures the operation of the plant into sequential steps. The entry point of the state machine is "Start". There is always only one active state. The active state checks the criteria pointing to the connected states and starts a transition if the logical expression of all criteria is true. Global states are special states that always check their entry criteria because of their high priority, which is used e.g. for safety technology. States can consist of substates. This is used to cluster states to visualize their coherence (e.g. to heat up the solar thermal system is always a part of the feed-in).

A criterion is based on measurements of physical values and durations. A duration can be based on a physical criterion (additional time criterion, "How long is a physical condition met") or on the active time of a state (τ_{State}, "How long is a state active"). The parameters of the criteria depend on the concrete plant and its constraints.

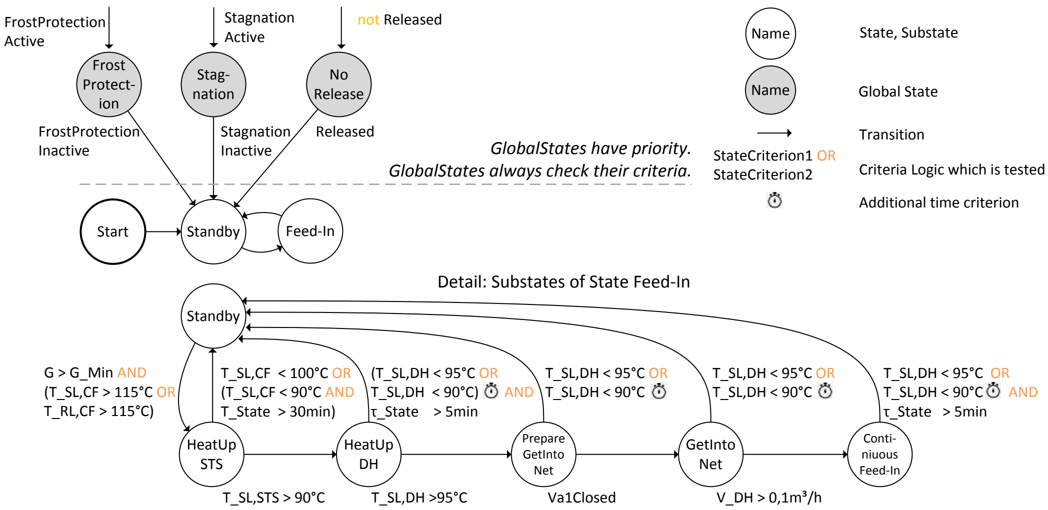

Fig. 3: State diagram of the net feed-in substation with detailed substates of the state Feed-in
Released – External release signal is true and feed-in allowed
G_Min – minimal radiation threshold calculated on basis of the collector curve
The criteria for Stagnation and Frost protection are discussed in the corresponding section.

Tab. 2: Description of the substates for the state Feed-in and controller activity (○ – inactive, ● - active)

State	Description	C1	C21	C22
Standby	Default State with no activity of the plant (night, cloudy day, winter day)	○	○	○
HeatUpSTS	When high temperatures are detected in the collector field, Pu_{STS} is activated and the hot fluid is moved into the network feed-in substation.	●	○	○
HeatUpDH	When the hot plug reaches the heat exchanger, the district heating side of the network feed-in substation is heated up by opening the bypass valve Va1 and starting the feed-in pump $Pu_{DH,F}$.	●	○	○
PrepareGetIntoNet	The bypass valve Va1 is closed.	●	○	○
GetIntoNet	The pump speed $Pu_{DH,F}$ rises until a volume flow $\dot{V}_{DH}$ is detected.	●	○	●
ContinuousFeed-In	Hot water heated by the collector field is fed into the district heating network	●	●	●

3.3 Measurement results

The exemplary measurement results of the state *Feed-in* (see Fig. 4) start at 8:00 of 22th of June and end at 18:00 with an average radiation of 530 W m^{-2} and an average ambient temperature of 31 °C.

The plant is operated according to the state machine described above with the substates from Tab. 2. In the morning, the system starts in *Standby* until $T_{CF,SL}$ or $T_{CF,RL}$ exceeds 115 °C. The collector field return line temperature $T_{RL,CF}$ is remarkable higher than the collector field supply line temperature mainly due to shading of C6. From 9:20 to 10:00 the active state falls back to *Standby*. The fallback is triggered by the low solar thermal supply line temperature $T_{SL,CF}$ < 90 °C criterion. This undesired behavior sometimes happens due to mentioned collector temperature variation during the heat up and is a specialty of the collector field design of the pilot plant. After reaching the state *HeatUpSTS* again the hot medium is transported to the heat exchanger and the district heating side gets heated up. During the *Continuous Feed-in* from 11:20 to 17:10 three different disturbances occur, which are well compensated. $T_{SL,DH}$ very accurately reaches its dynamic setpoint:

- 12:00, 15:50 – Peaks in the pressure difference Δp_{DH} are compensated by the pump speed adaption of the controller C22.
- 13:30 - The rising of the return line temperature $T_{RL,DH}$ by 10 K is compensated with a higher volume flow $\dot{V}_{DH}$ by the controller C21.
- 14:30 – The radiation starts to drop caused by clouds. The solar volume flow $\dot{V}_{STS}$ is reduced by the controller C1. The high thermal capacity of the collector and the medium as well reduces the sensitivity to radiation disturbances.

The continuous volatility of the district heating return line temperature $T_{RL,DH}$ is caused by the periodic opening and closing of the control valve of a district heating substation located in the long stub pipe to the district heating network.

In the evening the feed-in temperature $T_{SL,DH}$ falls below 95 °C and the feed-in is stopped by falling back to *Standby*. During the day 82 kWh solar thermal energy where fed into the district heating network mainly at the desired feed-in temperature of 110 °C. The current amount of heat fed into the network from January to September 2017 – without final optimization of the state machine and controller – is 8.556 kWh.

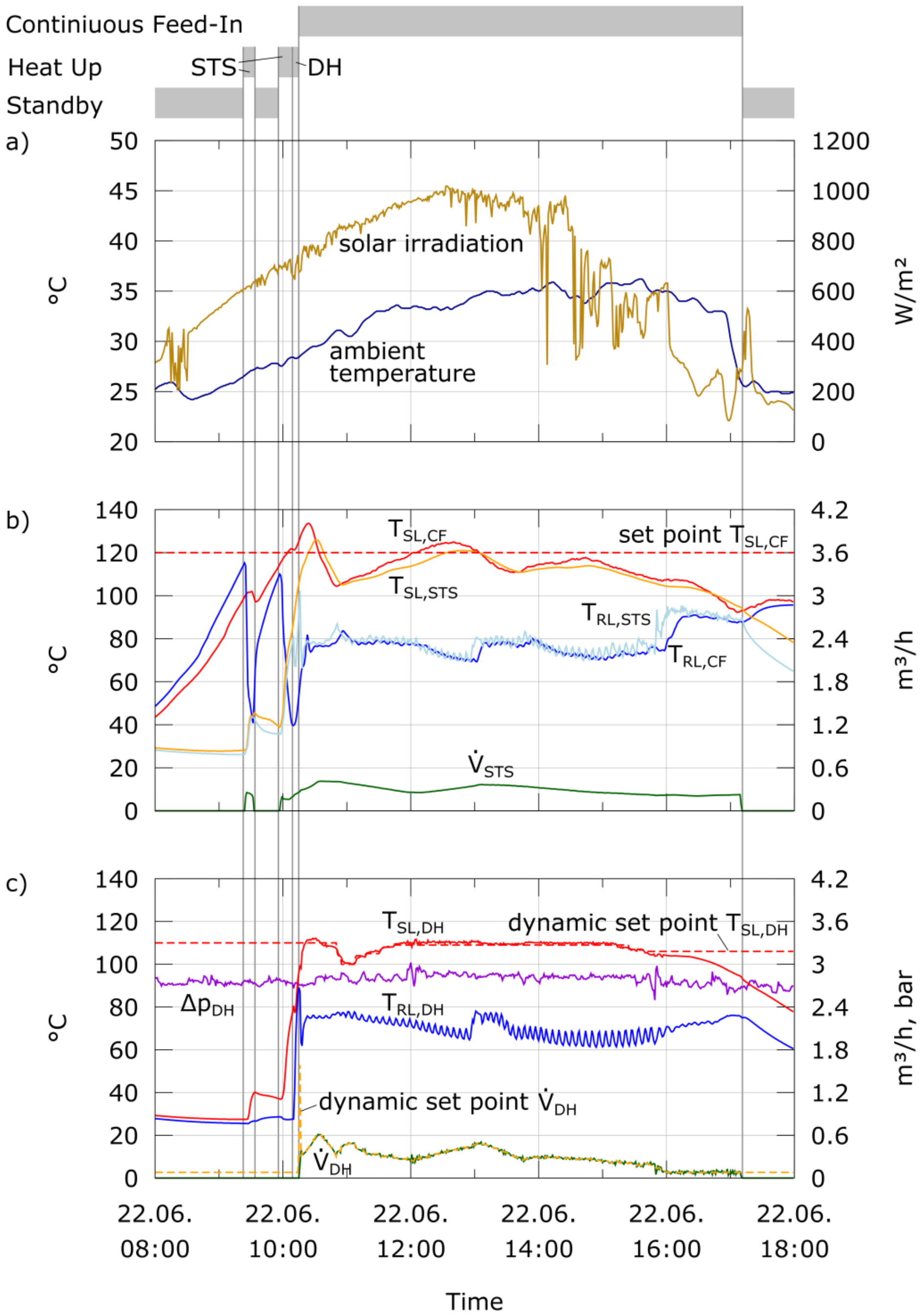

Fig. 4: Measurement data for state Feed-in,
a) ambient, b) solar system, c) district heating side

4. State Active Frost Protection

4.1 Controller and State Machine

The frost protection has to prevent all parts of the installation from cooling down to a temperature near the melting point of the solar liquid. To achieve this, a lower limit for the medium temperature in the solar system of 5 °C is defined. If any of the temperature criteria goes below this threshold, the state *Frost Protection* is activated. This state is defined as a global and is checked in every iteration.

If activated, heating water from the district heating return line flows through the district heating side of the station and back to the return line via the frost protection branch with the heat meter. The separate pump $Pu_{DH,FP}$ (see Fig. 1), which is installed in parallel to the feed-in pump $Pu_{DH,F}$, is used for this issue. The frost protection stops and returns to the *Standby* state, when all observed sensors exceed the upper threshold value of 10 °C and a minimum runtime is reached.

The tested variants concerning the details of the state *Frost Protection* made during the winter season 2016/2017 are shown in Tab. 3. First tests were done with the activation of the pumps when any of the collector field temperatures falls below the lower limit. These temperatures are reported by sensors installed in the piping of the supply and return line ($T_{SL,CF}$ $T_{RL,CF}$) and sensors in the connection pipes of the collector field (T_{HP}, $T_{Pipe,CF}$). The pumps are stopped if all measured temperatures go above the upper threshold. It has been shown, that a minimum runtime of 13 min is necessary to assure at least one turn of the fluid through the solar thermal system. Furthermore detailed evaluations using the DTS showed that under some conditions the collectors cool down faster than the piping of the collector field (see Rosemann, et. al., 2017b). Therefore two collector sensors CS (T_{C1}, T_{C4}) had been included in the scanning routine to detect low medium temperature within the collectors.

Tab. 3: Tested criteria for the de-/activation of the state Frost protection (○ – on, ● - off, | - "or", & - "and")

Name	Frost protection	Criteria	Pump activity Pu_{STS}	Pump activity $Pu_{DH,FP}$
5 °C	Enter	($T_{SL,CF}$ | $T_{RL,CF}$ | $T_{Pipe,CF}$ | T_{HP}) < 5 °C	●	●
	Exit	($T_{SL,CF}$ & $T_{RL,CF}$ & $T_{Pipe,CF}$ & T_{HP}) > 10 °C	○	○
5 °C, 13min	Enter	($T_{SL,CF}$ | $T_{RL,CF}$ | $T_{Pipe,CF}$ | T_{HP}) < 5 °C	●	●
	Exit	($T_{SL,CF}$ & $T_{RL,CF}$ & $T_{Pipe,CF}$ & T_{HP}) > 10 °C AND RUNTIME Pu_{STS} > 13 min	○	○
5 °C, 13min, CS	Enter	($T_{SL,CF}$ | $T_{RL,CF}$ | $T_{Pipe,CF}$ | T_{HP} | T_{C1} | T_{C4}) < 5 °C	●	●
	Exit	($T_{SL,CF}$ & $T_{RL,CF}$ & $T_{Pipe,CF}$ & T_{HP} & T_{C1} & T_{C4}) > 10 °C AND RUNTIME Pu_{STS}> 13 min	○	○

4.2 Measurement results

In Fig. 5 the measurement data for the operation of the frost protection using the latest level of development are shown (5°C. 13min, CS). The measurement period starts at midday of the 8th of February and ends at midday the day after. The average ambient temperature was -2.7 °C, at minimum -4.7 °C and the sky was clouded. The upper chart illustrates temperature profiles gained from the sensors of the solar thermal system and the collector field. The lower chart contains the temperature values on the district heating side.

The temperatures in the collector field increase in the afternoon due to solar gains and are dropping constantly afterwards. The solar gains only effect the sensors located directly next to the collectors. The temperature in the 25 m long connection pipe between C1 and C2 $T_{Pipe,CF}$ is not raised. At 19:50 $T_{Pipe,CF}$ triggers the first frost protection period (#1). All other frost protection periods (#2 to #4) are triggered by the collector sensor T_{C4}.

The solar pump operates at its maximum speed ($\dot{V}_{STS}$) when the state *Frost Protection* is active. The volume flow on the district heating side $\dot{V}_{DH}$ is controlled in order to reach a supply line temperature of 20 °C in the solar circuit. The temperatures on the district heating side $T_{RL,DH}$ and $T_{SL,DH}$ are very low, almost at room temperature.

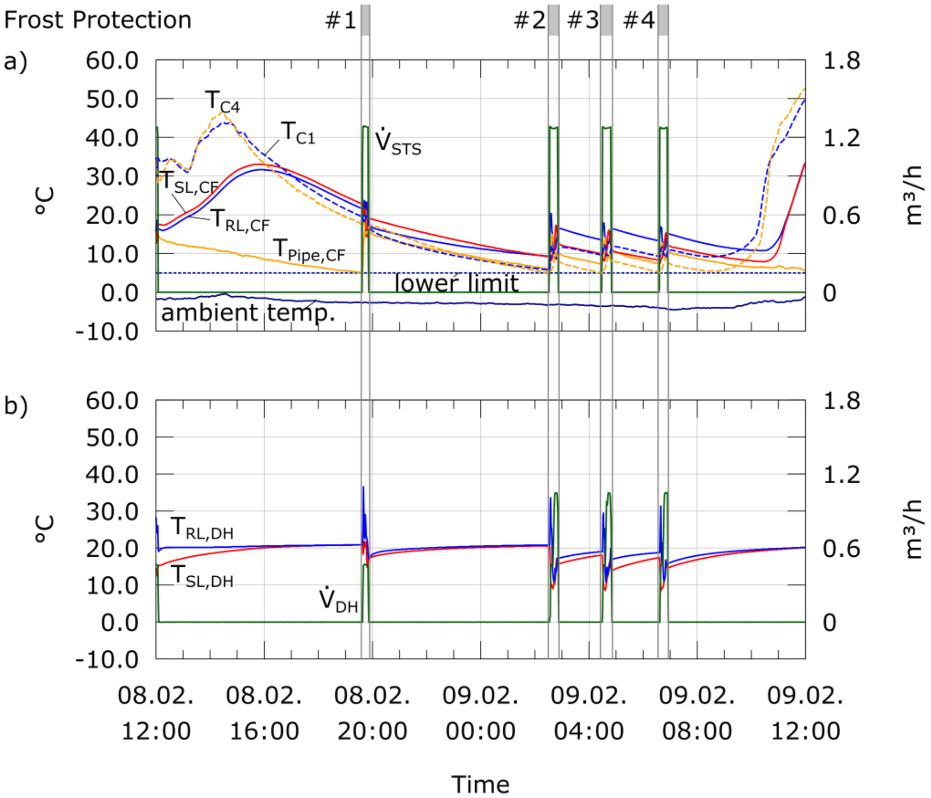

Fig. 5: Measurement data for state Frost Protection, a) solar system, b) district heating side

The solar thermal plant is connected to the district heating network via a long stub pipe. In the presented time period the connected consumers have no heat demand and the return line cools down. The frost protection can be guaranteed anyway, because it's little heat demand and the big transfer surface of the heat exchanger. Overall a heat demand for the frost protection of 4 kWh was measured at that day.

Fig. 6 shows the daily heat demand for the frost protection over the daily ambient temperature for the whole winter season. Days with a relatively high irradiation (> 1,2 kWh/m² in collector plane) are colored red, others blue. As expected the heat demand for frost protection increases with decreasing ambient temperatures. This demand is clearly reduced at days with high solar gains. The frost protection starts at daily average ambient temperatures of about 3 to 5 °C. The heat demand can go up to 14 kWh per day at very cold days with daily average ambient temperatures under -5 °C.

For the optimized and save variant of the state *Frost Protection* (× 5 °C, 13min, CS) only 9 days with a heat demand are available. The heat demand added up to 273 kWh for the whole winter season, which is about 2 – 3% of the annual heat output fed into the district heating system. This is in the range of known plants with active frost protection.

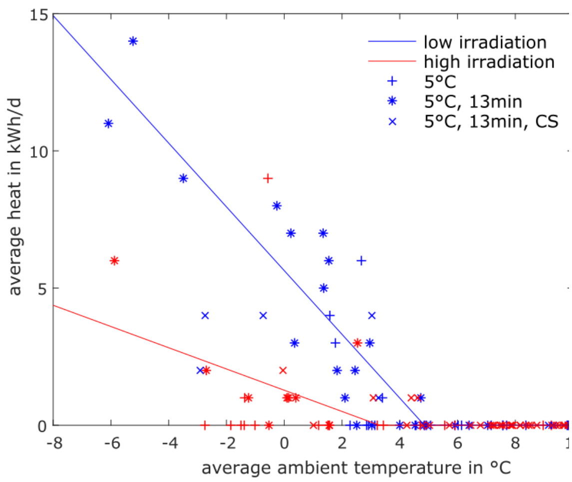

Fig. 6: Statistical evaluation of the frost protection season in winter 2016/17, daily average, low irradiation < 1,2 kWh/m² in collector plane per day ≤ high irradiation

5. State Stagnation

5.1 Controller and State Machine

The operation of a solar thermal system can stop during the day even though there is a solar irradiation. This can occur because of a case of damage, a plant maintenance or the operator of the district heating network withdraws the release signal. The stagnation concept has to ensure an intrinsic safety of the installation to handle this issue. Stagnation is detected by the state machine observing the collector field supply line temperature $T_{SL,CF}$. If it exceeds the limit of 138 °C for more than 5 min or if it exceeds 140 °C the state *Stagnation* is activated. This mainly stops the solar circulation pump. No other switching operation is necessary. The stagnation cooler should limit the produced steam volume and the compressor pressure maintenance should take this volume and keep the pressure in the tolerated range.

The state *Stagnation* is left when $T_{SL,CF}$ falls below 120 °C for more than 5 min or under 110 °C. The *Stagnation* state is implemented as global state.

5.2 Measurement results

Fig. 7 shows a test of the state *Stagnation* at the 5th of September 2017. It was a warm (up to 25 °C) and sunny day with some clouds during midday (maximum 1000W/m² in collector surface). Subfigure a) shows ambient conditions, Subfigure b) pressures at the lowest and highest point in the system (p_{LP}, p_{HP}) and the filling level of the expansion vessel (V_{PM}). Subfigure c) includes temperatures of the collector field (where T_{C6} is measured with the DTS), the calculated boiling temperature under the conditions at the highest point and the volume flow in the solar thermal system $\dot{V}_{STS}$. Subfigure d) is a carpet plot of the DTS with the time on the x-axis and the position in the collector field on the y-axis. The temperature is color coded (dark-blue means cold, light-blue means feed-in temperature, green means boiling temperature, red means superheated steam).

In the morning the system starts in *Standby* until one temperature of the collector field exceeds 115 °C. From 10:00 to 10:50 the solar and afterward the district heating side is heated up followed by the state *Feed-In*. At 12:00 the release signal is withdrawn manually and the system changes to *Standby*. At about 13:00 the state machine recognizes the state *Stagnation*. Using the DTS, which can measure the temperature not only at discrete locations, the boiling temperature is already reached at 12:30 in C5 and C6. The filling level sensor V_{PM} also recognizes a fast increase from 14 to 28% at this point in time, which means that first steam is produced here. Solar liquid displaced by the spreading steam bubble can only flow in the direction of the supply line into the pressure maintenance due to the plant configuration.

The equalizing of the pressure values at the highest p_{HP} and lowest point p_{LP} in the system between 12:30 and 13:00 is very interesting. This results from the falling water level when the steam fills the supply line and finally reaches the stagnation cooler at the lowest point. The pressure maintenance keeps the pressure level at the lowest point constant and thus increases the pressure at the top of the system p_{HP}. This behavior can reduce the dynamic of the beginning stagnation because the boiling temperature is slightly increased.

According to subfigure d) at about 13:00 the boiling point is reached in all collectors and all connection pipes between C2 and C6. When C1 is filled with steam a steam front fills about 8 m of the connection pipe between C1 and C2. The cool water in the connection pipe is pushed in C2 and C3 and temporary causes a condensation here. When the steady state is reached in C1 the steam front in the connection pipe condenses again and sucks in steam from C2 into the connection pipe. At first in C1 the steam is superheating, because here are the lowest dynamics. Shortly before 15:00 the superheating also occurs in C5 and C6 and at 16:00 in C4. In C2 and C3 there is boiling liquid for the whole measurement day.

At 16:30 the maximum filling level of the expansion vessel is reached with 65%. The stagnation cooler can safely limit the produced volume of steam. The solar irradiation is decreasing in the evening hours. Starting from 17:30 the steam front is declining, which makes the pressure at the highest point p_{HP} decrease again. At 18:15 subcooled liquid reaches the collector field and the steam condenses very fast and empties the expansion vessel. This causes a short and small underrun of the allowed pressure level p_{LP}. The state *Stagnation* is left.

The presented stagnation test (and several others) shows that the *Stagnation* state can be handled safely. Produced steam is condensed in the stagnation cooler. The compressor pressure maintenance can take all of the produced steam volume and can mostly keep the pressure in the desired range.

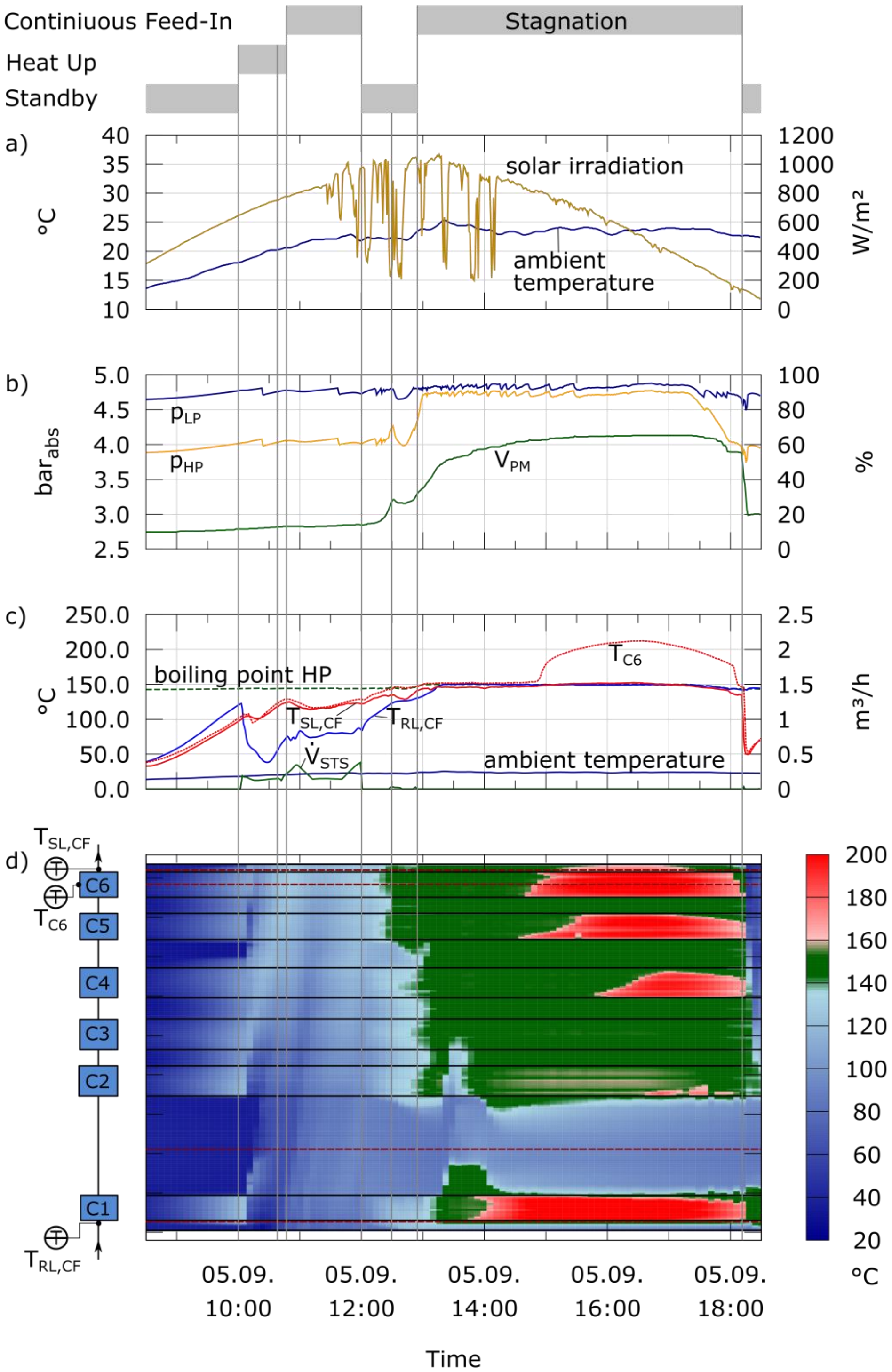

Fig. 7: Measurement data for stagnation, a) ambient, b) pressure maintenance, c) solar system, d) DTS of the collector field

6. Conclusions/Prospects

The planning of the pilot plant, the realization and the operating experience of almost one year have already provided valuable information which can be used for standardization of decentralized feed-in substations. There is a need for clarification with the district heating companies regarding the control accuracy of the feed-in temperatures. A high control accuracy of the feed-in temperature always is reached at the expense of a higher variation of the feed-in volume flow and vice versa. For solar thermal systems, a higher temperature tolerance especially in the morning during heat up or during phases of clouds would ease the general operation. Especially for district heating systems with a crucial solar fraction a high variation of the feed-in volume flow can cause hydraulic problems and interference.

The use of water as solar liquid is feasible with an active frost protection in the winter season. It is necessary to take the different cooling behavior of the collectors and the piping into consideration. A well designed separate stagnation cooler combined with a small additional auxiliary vessel can safely limit the steam spread and protect the membrane of the expansion vessel. This combination can reduce the design volume of the expansion vessel thus reduce investment costs.

Solar thermal gain prognoses will be possible after the validation of a simulation model for the decentralized solar thermal feed-in substations. It is intended to make simulations studies regarding the generalization of the current control concept (state machine) and a model predictive control concept. The commissioning of a combined supply and feed-in substation connected to a low temperature district heating network in Berlin Adlershof[1] is in progress. This will extent the monitoring portfolio of the research project.

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[1] Founded by Federal Ministry for Economic Affairs and Energy FKZ 03ET1155B.

8. Appendix: Units and Symbols

Table 4: Symbols

Quantity	Symbol	Unit
Area	A	m^2
Global irradiance or solar flux density	G	$W\ m^{-2}$
System mass	m	kg
Mass flow rate	$\dot{m}$	$kg\ s^{-1}$
Pressure (absolute)	p	bar
Pressure difference	Δp	bar
Heat	Q	kWh
Heat flow rate	$\dot{Q}$	kW
Temperature	T	°C
Efficiency	η	
Time	τ	s

Table 5: Abbreviations and subscripts

Quantity	Symbol
Ambient	a
Collector	Col
Collector field	CF
Collector sensor	CS
District heating	DH
Feed-in	F
Frost protection	FP
Heat meter	HM
Highest point in system	HP
Lowest point in system	LP
Network feed-in Substation	NFS
Pressure maintenance	PM
Pump	Pu
Return line	RL
Valve	Va
Solar thermal system	STS
Supply line	SL